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Globular clusters in the outer halo of M31: the survey

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ABSTRACT

We report the discovery of 40 new globular clusters (GCs) that have been found in surveys of the halo of M31 based on INT/WFC and CHFT/Megacam imagery. A subset of these these new GCs are of an extended, diffuse nature, and include those already found in Huxor et al. (2005). The search strategy is described and basic positional and V and I photometric data are presented for each cluster. For a subset of these clusters, K-band photometry is also given. The new clusters continue to be found to the limit of the survey area (~ 100 kpc), revealing that the GC system of M31 is much more extended than previously realised. The new clusters increase the total number of confirmed GCs in M31 by approximately 10% and the number of confirmed GCs beyond 1° (≈ 14 kpc) by more than 75%. We have also used the survey imagery as well recent HST archival data to update the Revised Bologna Catalogue (RBC) of M31 globular clusters.

Key words: galaxies: star clusters – galaxies: formation – galaxies: evolution – galaxies: individual (M31) – galaxies: haloes

1 INTRODUCTION

Globular cluster (GC) systems provide fossil signatures with which to untangle the history of galaxy formation. GCs are gravitationally bound concentrations of (typically) between 10^4 to 10^6 stars, and it is believed that they were among the first objects to be formed in a galaxy, and so provide insight into the formative stages of the host (see the review by Brodie & Strader 2006). There is also strong evidence that they form in major galaxy interactions and mergers, and so can trace such events (e.g. Whitmore & Schweizer 1995). Since GCs most are believed to comprise stellar populations of a single age and abundance (some unusual GCs, such as ω Cen and NGC 2808 exhibit multiple populations - Bedin et al. 2004; Piotto et al. 2007), their colour-magnitude diagrams (CMDs) provide a particularly powerful tool with which to age-date significant events in a galaxy's history. Indeed, the presence of various sub-populations within a GC system is widely interpreted as indicating distinct epochs of mass accretion and/or major star formation (West et al. 2004).

In the case of the Milky Way, accretion events appear to have played an important role in shaping the GC system. Perhaps as many as eight of the Milky Way halo GCs beyond a galactocentric radius $R_{GC} \gtrsim 10$ kpc ($\sim 20\%$ of the population) are associated with the Sagittarius dwarf spheroidal and its tidal stream (Bellazzini, Ferraro, & Ibata 2003; Sbordone et al. 2005; Tautvaišienė et al. 2004), attesting to the fact that even relatively minor accretion events can significantly augment the globular cluster population of the parent galaxy. A further group of GCs and open clusters has been identified as having a possible origin in the putative dwarf galaxy remnant in Canis Major (Martin et al. 2004), although at least one of these (NGC 2808) has since been shown to not be a member, from its orbit (Casetti-Dinescu et al. 2007). Spatial alignments of Oosterhoff subpopulations amongst other outer Milky Way GCs suggest that many more may have been captured from accreted dwarfs (e.g. Yoon & Lee 2002). It would be valuable to discover if other galaxies have evidence of comparable GC accretion.

The only large GC systems (more than 100 clusters) whose members can be cleanly resolved into stars (and hence plotted on CMDs) with current technology belong to the Milky Way (MW) and M31. The GC system of M31 is of particular interest since it allows for a direct comparison between ages and metallicities derived from resolved stellar population studies with HST, and from studies of integrated

light. Moreover, as the nearest large spiral, M31 provides a means to test how representative the Milky Way's GC system is of large spirals in general.

Brodie & Strader (2006) have summarised some of the major properties of the M31 GC system, as part of their larger review on extragalactic GC systems. They conclude that the GC system of M31 to be quite substantial, estimated at about 450 ± 100 members, which is a factor of ~ 3 greater than that of our own Galaxy. To a first approximation, the M31 GC luminosity distribution is similar to that of the MW in being well-approximated by a Gaussian, although the details of the turnover magnitude and dispersion may differ somewhat. The M31 GC system also contains a metal-rich and a metal-poor component, which are tentatively identified as analogues to the MW disk-halo (or more recently bulge-halo) GC populations (Barmby et al. 2000). Early work by van den Bergh (1969) hinted at a bimodal metallicity distribution in the M31 GC population. Spectroscopy by Perrett et al. (2002) confirmed this bimodality, with the peaks at [Fe/H] = -1.44 and -0.50 dex. Of their 301 GCs with spectroscopic metallicities, they find 70 (i.e. 23%) to be attributable to the metal-rich population. Perrett et al. (2002) also present evidence for a slight metallicity gradient in the metal-poor population, which, although consistent with a scenario of early dissipational collapse, does not preclude other models. There is also a correlation between the rotation of the GC populations and metallicity, first identified by van den Bergh (1969). More recently Perrett et al. (2002) have further shown that the metal-rich GCs are centrally concentrated, with significant rotation (160 km s^{-1}), and are consistent with a bulge population. The metal-poor cluster system is more spatially extended, as expected for a halo population, and intriguingly also exhibits rotation (131 km s^{-1}). These results While the MW and the M31 GC systems share many common properties, recent work has suggested that M31, unlike the MW, may host a population of young GCs (Puzia, Perrett, & Bridges 2005; Beasley et al. 2004; Burstein et al. 2004; Fusi Pecci et al. 2005). If confirmed, such a population could place interesting constraints on the merger history of M31.

To date, the study of M31 GCs has been largely based on the excellent Bologna Catalogue, which is frequently revised. Updates on the original Revised Bologna Catalogue (RBC) of M31 GCs (Galleti et al. 2004a) were recently published (Galleti et al. 2006, 2007). The RBC consists of the original Bologna Catalogue (Battistini et al. 1987) supplemented with candidates from Battistini et al. (1993), Auriere, Coupinot, & Hecquet (1992), Mochejska et al. (1998) and the HST archive work of Barmby & Huchra (2001). Since it is based on the original Bologna Catalogue (Battistini et al. 1987) which is taken from a 3 x 3 square degree region around the centre of M31, the Revised Catalogue is also mainly concentrated within these limits, i.e. a projected galactocentric distance less than about 30 kpc (throughout this paper we assume a distance to M31 of ~780 kpc, McConnachie et al. 2005). However we find globular clusters at much greater galactocentric distances (e.g. AM 1 at more than 120 kpc) from the centre of the MW, the most comparable galaxy, suggesting that many undiscovered GCs may lie beyond the Catalogue limits. Many of the RBC candidates have been selected from previous surveys based on photographic plates and contamination has proved a significant problem. For example, Racine (1991) found from high-resolution CFHT imaging that of 107 Bologna Catalogue candidates, only 51 were genuine globular clusters. This is in spite of the fact that he only chose candidates well away from the main disk of M31 to avoid problems of crowding, extinction and reddening. Spectroscopic (e.g. Barmby et al. 2000; Perrett et al. 2002) and imaging confirmation of many candidates has been undertaken for the main disk region, and along the major and minor axes, but little has been done for other regions, except for serendipitous HST imaging as part of a programme looking at background field galaxies (Barmby & Huchra 2001).

We present here a new search for GCs in the halo of M31, based on new deep, wide-field imaging surveys undertaken at the INT and CFHT. In the past few years, our group has been conducting a long-term study of M31, using both ground-based and space-based instruments. These surveys have led to the the discovery of many significant features in M31 including copious low surface brightness substructure (Ibata et al. 2001; Ferguson et al. 2005; Ibata et al. 2007), an extended metal poor stellar halo (Chapman et al. 2006), a giant rotating structure (Ibata et al. 2005) and several new dwarf galaxies (Chapman et al. 2005; Martin et al. 2006; Ibata et al. 2007). Early results from the search for new M31 GCs from these data were published in Huxor et al. (2004, 2005).

2 THE SEARCH FOR M31 CLUSTERS

2.1 The data

The images and catalogues employed in this study were taken from two different ground-based surveys. The majority of the data were taken as part of the Isaac Newton Wide Field Camera survey of M31 conducted during the period 2000-2005. Exposures of 800-1000 seconds were taken in the Johnson V and Gunn i bands, reaching (average 5 σ) limiting magnitudes of i = 23.5 and V =24.5. The average seeing was generally better than $1.2''$. The fields observed include an area far into the halo, and an additional region south along the Andromeda Stream (Ibata, Gilmore, & Irwin 1995) towards M33. The survey data were processed by the INT WFS pipeline (Irwin & Lewis 2001) provided by the Cambridge Astronomical Survey Unit; this pipeline provides astrometry, photometry and object description and classification (i.e. whether the object is stellar, non-stellar or noise). The INT/WFC fields that cover the bright part of the M31 disk were not used in the search for new GCs due to the high degree of crowding present in these regions. The second dataset was taken from out still ongoing Canada France Hawaii Telescope survey of the M31 far outer halo using Megacam. Exposures of 5×290 seconds were taken in each of the g and i bands with seeing typically better than $0.8''$. Full details of these surveys can be found in Ferguson et al. (2002) for the INT/WFC data, and in Ibata et al. (2007) for the CFHT/Megacam data. We utilize the full INT WFC survey area corresponding to 60 square degrees but only 24 square degrees of the Megacam survey area. This is due to the fact that only part of the latter dataset was in hand at the time that our GC search was undertaken.

2.2 The Strategy for Classical GCs

In the Milky Way, star clusters are well resolved so searches for new GCs can be based solely on star count density enhancements (e.g. Drake 2005). However, for most external galaxies, GCs are unresolved and hence other search methods must be utilised. The most common approach to identifying extragalactic GC candidates is to use magnitude and colour information, as GCs have magnitudes and colours that are expected to fit within a limited range. Additionally, shape parameters such as size and ellipticity can also be used. An example of this approach is provided by Sharina, Puzia, & Makarov (2005) in their search for GC candidates in nearby (2 - 6 Mpc) dwarf galaxies. Typically these searches adopt criteria based on MW GC templates and thus have the inherent weakness of not probing other regions of parameter space. That is, our view of what constitutes a globular cluster will be biased towards objects that are similar to the GCs found in our own Galaxy.

In very nearby galaxies, GCs are expected to be more extended than the stellar PSF. Kim, Sung, & Lee (2002), for example, use the two radial moments r_1 and r_{-2} which characterize the image wing spread and the image central concentration respectively. A variant of this approach has been recently employed by Gómez et al. (2006) in their search for GCs in NGC 5128. They subtract the stellar PSF from all the sources in their frames, and visually inspect the residuals. Extended objects leave a "doughnut-shape", as they are under-subtracted in the wings and over-subtracted in the centre. Similarly, Galleti et al. (2004b) use this technique to locate GCs in NGC 253. However, PSF subtraction will also reveal compact background galaxies as well as GCs hence additional rejection methods must be employed.

In more distant galaxies, the only method available is to search for a statistical over-density of objects with the characteristics of GCs (van den Bergh & Harris 1982). This places constraints on the overall number density and spatial extent of a GC system without being certain of the status of any specific object. Control fields are usually observed to obtain a background count, or alternatively, published counts for likely contaminants, such as galaxies, can be used (Liller & Alcaino 1983). One of the early applications of this approach was in the hunt for M31 GCs (Wirth, Smarr, & Bruno 1985).

Extragalactic GC candidates usually require spectroscopic confirmation, where possible, since the risk of false positives is high with the techniques discussed above. For example, Beasley & Sharples (2000) undertook spectroscopic follow-up of 103 published GC candidates in the Sculptor group galaxies NGC 253 and NGC 55. The candidates had been selected on the basis of colour, magnitude and galactocentric distance (R_{gc}) cuts, however, only 14 genuine GCs in NGC253 and one probable GC in NGC 55 were actually confirmed.

Our search for M31 halo clusters exploits the fact that GCs at this distance should be just resolved in good seeing. In fact, given the survey depths, one should even be able to resolve stars to below the tip of the red giant branch (TRGB) in M31 clusters, enabling direct detection of the brightest individual red giants. Confining the search to the halo also means that the patchy extinction and rapidly fluctuating light levels in the main body of M31 are not a concern. For the INT/WFC survey, GC candidate selection was based on magnitude, colour, ellipticity, object classification (stellar/non-stellar) and image width (scale size), all of which are provided by the photometric pipeline. GCs are known to inhabit a specific range of absolute magnitudes, $-10.5 < V < -3.5$ (equivalent to apparent V magnitudes of $14 < V < 21$ at the distance of M31), and colours, $0 < (V - I) < 1.7$. The generous values, for both magnitude and colour, were chosen so as to allow for errors. This conservative approach was chosen to avoid excluding any possible GCs from the candidate list generated (but even these parameters finally proved over-constraining, see the following section). Ellipticity was used as a criterion (< 0.3) to eliminate many field galaxies, and finally the image width (having a Gaussian $\sigma > 2.5$ pixels, which for the INT/WFC is equivalent to ≈ 0.85 arcsec - comparable to the best seeing in the survey images) of objects was employed to remove the bulk of stars. These cuts were tested against the then confirmed M31 GCs to ensure that none were excluded[1] For the CFHT/Megacam survey, the search was based on magnitude and colour cuts alone as the greater resolution of Megacam allows better visual identification of GC candidates. The same magnitude limits were used for the g and i band employed by CFHT/Megacam as the conservative V and I values allowed for the conversion to g and i. All GC candidates were then visually inspected for morphological evidence of cluster status and, if confirmed as a cluster, cross-checked against the Revised Bologna Catalogue (http://www.bo.astro.it/M31/; Galleti et al. 2004a, 2006, 2007) to determine if they were previously known. Our search has resulted in the discovery of 27 new "compact" GCs in the halo of M31. The V and g images of these clusters are shown in Figures 1 and 2 and their basic positional and photometric properties are listed in Table 1 (note that the H prefix indicates "halo" GC). Nine of these new clusters were initially presented in a short conference paper (Huxor et al. 2004). This sample included one cluster (H6) which was subsequently rediscovered by Galleti et al. (2005) who gave it an RBC designation of B514. Mackey et al. (2007) have recently presented deep HST/ACS imagery for a subsample of these classical GCs which they use to derive metallicities, structural parameters and horizontal branch morphologies; the GC IDs used in that paper are listed in column 6 of Table 1.

We note that much recent work on extragalactic GCs has preferred the use of colours that are more sensitive to metallicity, such as (B-V) and (B-I) over (V-I), or variants on the Washington system (e.g. Dirsch et al. 2003), and (V-K) optical/NIR colours (e.g. Puzia et al. 2002). These are the bands of choice when the aim is to obtain age and metallicity measures. In the study presented here, we are constrained to the existing V- (or g-) and i-band images that have been taken as part of a larger general-purpose survey. However, the failings of (V-I) over these other systems is less

[1] We are grateful to the anonymous referee for pointing out that GCs with a ellipticities > 0.3 have been found in NGC 5128 [Harris et al. 2006]. This result was published after our search had been undertaken, and it is possible that very elliptical halo M31 GCs may await discovery.

Table 1. Properties of the New Classical Globular Clusters. The V magnitude was obtained for a eight arcsec aperture radius, the (V - I) colour for a smaller six arcsec aperture.

ID	RA(J2000)	Dec(J2000)	V	(V-I)	M07 ID[a]
H1	00 26 47.80	+39 44 46.7	16.05	0.98	GC1
H2	00 28 03.28	+40 02 56.2	17.58	0.94	
H3	00 29 30.15	+41 50 32.1	18.13	1.16	
H4	00 29 45.01	+41 13 09.6	16.98	0.94	GC2
H5	00 30 27.30	+41 36 20.0	16.31	0.95	GC3
H6	00 31 09.85	+37 54 00.4	15.76	1.08	GC4
H7	00 31 54.55	+40 06 47.8	18.10	1.09	
H8	00 34 15.44	+39 52 53.2	19.62	1.24	
H9	00 34 17.29	+37 30 43.3	17.62	0.94	
H10	00 35 59.76	+35 41 03.9	16.09	1.08	GC5
H11	00 37 28.12	+44 11 25.0	16.88	0.96	
H12	00 38 03.87	+37 44 00.7	16.47	0.97	
H13	00 38 33.65	+41 44 53.1	-	- [b]	
H14	00 38 49.39	+42 22 47.1	18.27	1.20	GC7
H15	00 40 13.20	+35 52 36.6	17.99	0.84	
H16	00 40 37.80	+39 45 29.9	17.53	0.92	
H17	00 42 23.68	+37 14 35.0	17.37	0.97	
H18	00 43 36.03	+44 58 59.3	16.64	0.98	
H19	00 44 14.88	+38 25 42.2	17.35	0.96	
H20	00 45 52.51	+39 55 52.3	18.63	0.85	
H21	00 48 50.57	+41 08 36.5	18.69	1.06	
H22	00 49 44.69	+38 18 37.4	17.03	0.99	
H23	00 54 25.02	+39 42 55.3	16.72	1.04	GC8
H24	00 55 43.94	+42 46 16.2	17.78	1.07	GC9
H25	00 59 34.56	+44 05 39.1	17.29	1.47	
H26	00 59 27.37	+37 41 34.1	16.96	0.98	
H27	01 07 26.30	+35 46 46.5	16.50	0.91	GC10

[a] IDs used by Mackey et al. (2007).
[b] Cluster overlapped by bright star making photometry impossible

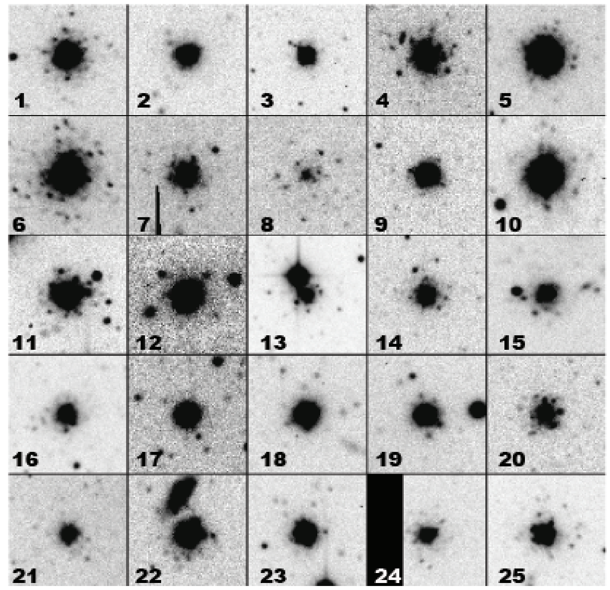

Figure 1. V-band images of the new clusters from the INT data. Each image is 30 x 30 arcsec. They are in RA order (from H1 to H25) left to right and top down. One cluster is a partial image as it lies on the edge of the chip, and one (in the centre of the mosaic) overlaps the image of a nearby bright star.

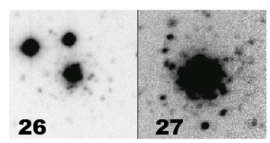

Figure 2. g-band images of the new clusters from the Megacam data. Each image is also 30 x 30 arcsec.

important, as our aim here is simply to find candidates for follow-up observations.

2.3 The Strategy for Extended Clusters

While undertaking aperture photometry of one of the newly-discovered classical GCs, a diffuse cluster was serendipitously discovered nearby in the same field. Since this object had been partially deblended by the INT/WFC pipeline, it had been missed by the semi-automated approach employed in the main GC survey. This object was significantly more extended than typical GCs with a half-light radius (R_h) of 35 pc . This discovery subsequently prompted a visual survey of all the INT/WFC and CFHT/Meegacam images to be undertaken, which resulted in the discovery of 13 further objects with similar "extended" properties (see Figure 3). Huxor et al. (2005) presented the first extended clusters found in M31 while Mackey et al. (2006) have presented deep HST/ACS CMDs for four such systems.

It is interesting to speculate as to why these extended clusters were not uncovered in previous GC searches of M31. Most of the earlier surveys concentrated on the main disk area of M31, and the high surface brightness background and stellar crowding would make the discovery of such faint and extended objects difficult. These problems would not be present in halo searches, however the sensitivity and spatial extent of previous surveys (many of them based on photographic plates) would neither reveal them nor their nature. Three extended clusters from this sample have already been published (Huxor et al. 2005), along with King model profile fits. These (HEC5, HEC7 and HEC4) are the most luminous of the extended clusters, yet only have V-band surface brightnesses within the half-light radius of 23.9, 22.6 and 24.0 mags arcsec^{-1} respectively, making them hard to distinguish from a background low-surface brightness galaxy.

The basic properties of the extended clusters are listed in Table 2. Being more extended than the objects in Table 1, the ID numbers have the prefix HEC to indicate that they are "halo extended cluster". The extended nature of these clusters makes them very interesting; some of them are larger for their luminosity than any known GCs and start to encroach on a region of R_h–M$_V$ parameter space normally inhabited by dwarf spheroidal galaxies .

In total, we have found 40 new clusters in the halo of M31. Using the latest Revised Bologna Catalogue (taking the Galleti et al. (2006) revisions and those in Table 4 into account), the new clusters represent an increase of more than 10% of the total confirmed sample, and an increase of more than a 75% of those known beyond 60′(≈ 14 kpc). This very significant improvement in the sample of clusters at large radius enables a much better analysis of the features of the

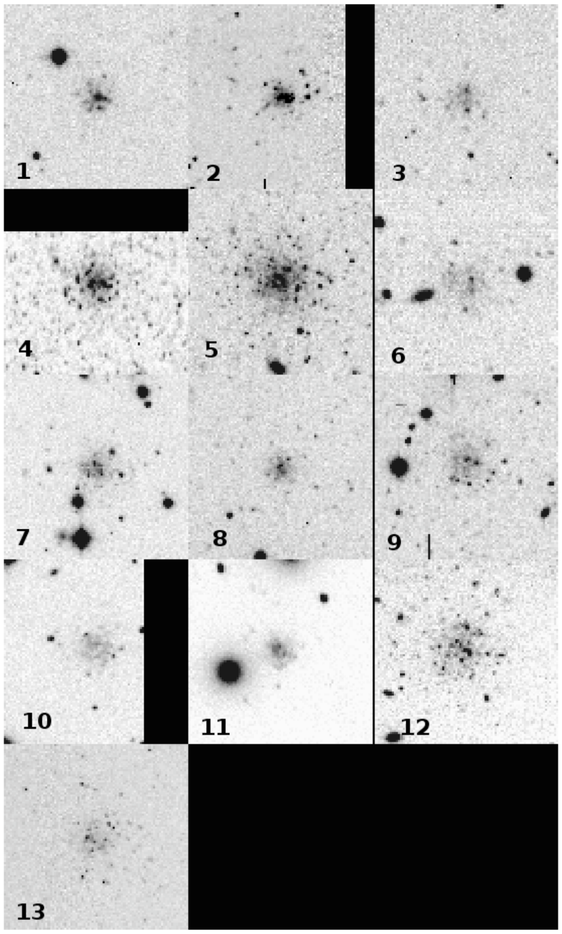

Figure 3. V band (g band for clusters 2, 12 and 13, which are only present in the CHFT/Megacam survey area) images of the extended clusters. Fields are 1 arcmin × 1 arcmin. The numbers indicate the ID.

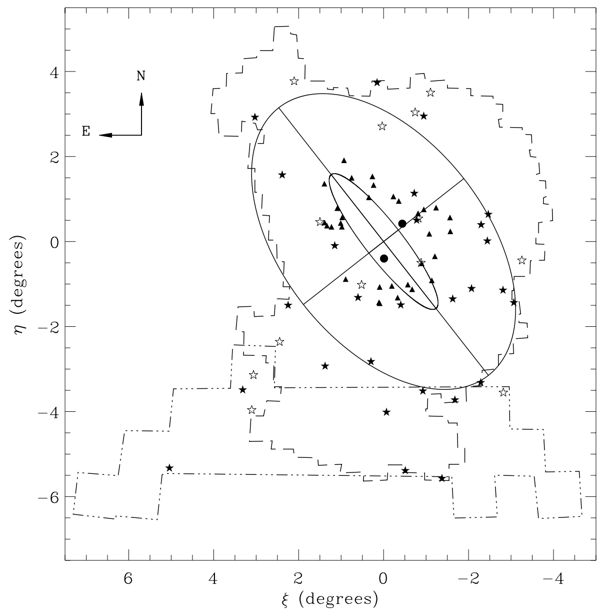

Figure 4. The location of the new globular clusters (filled stars) and extended clusters (open stars) in relation to confirmed RBC GCs that lie in our survey area (black triangles; the remaining RBC GCs are not shown), to show the limited extent of the known GC population prior to this study. The major landmarks (the satellite galaxies M32 and NGC 205 are also shown (large filled circles). The dashed line outlines the INT survey area covered, and the dashed-dotted line outlines that part of the Megacam survey employed. The inner ellipse has a semimajor axis of 2° (27 kpc) representing a disk with an inclination of 77.5°; the optical disk of M31 lies well within this boundary. The outer ellipse denotes a flattened ellipsoid of semimajor axis length 4° (55 kpc). Note that the relatively large size of the WFC fields result in a number of known GCs within the inner ellipse being found in our survey area.

Table 2. Basic Properties of the New Extended Clusters

ID	RA(J2000)	Dec(J2000)	V	(V-I)	M06 ID[a]
HEC1	00 25 33.96	+40 43 39.4	18.44	0.49	
HEC2	00 28 31.65	+37 31 24.4	19.17	1.07	
HEC3	00 36 31.72	+44 44 16.7	19.62	1.10	
HEC4	00 38 04.60	+40 44 39.0	17.60	1.02	EC3
HEC5	00 38 19.50	+41 47 15.0	17.60	0.88	EC1
HEC6	00 38 35.60	+44 16 49.0	18.99	1.05	
HEC7	00 42 55.00	+43 57 28.0	17.10	0.93	EC2
HEC8	00 45 26.90	+40 13 47.0	19.19	1.28	
HEC9	00 50 45.88	+41 41 34.6	18.65	1.04	
HEC10	00 54 36.40	+44 58 44.2	18.77	1.00	
HEC11	00 55 17.32	+38 51 02.5	17.69	1.00	
HEC12	00 58 15.42	+38 03 02.0	18.84	1.07	EC4
HEC13	00 58 16.93	+37 13 50.9	19.60	0.81	

[a] IDs used by Mackey et al. (2006).

halo GC system, and this will be described a follow-up paper (Huxor et al. in prep).

We note that the new clusters – both the classical and extended types – are found very far from M31 (see Figure 4). They extend far beyond the limits of previously "confirmed" GCs or the spectroscopically confirmed sample of Perrett et al. (2002). Indeed, they are found in all regions that have been surveyed to date (up to ∼ 100 kpc), suggesting that yet more are likely to be discovered as the survey areas are extended in future.

2.4 Photometic Properties

2.4.1 Optical Photometry

Integrated photometry of the new GCs was undertaken with the IRAF task apphot. Table 1 lists the uncorrected Johnson V magnitudes which have been measured within an aperture of 8″radius except for clusters H12 and H16. The former is merged with a bright star and has no photometry, while the latter has a value determined at the edge of a CCD frame. The image for cluster H7 was first masked to remove the

[h]

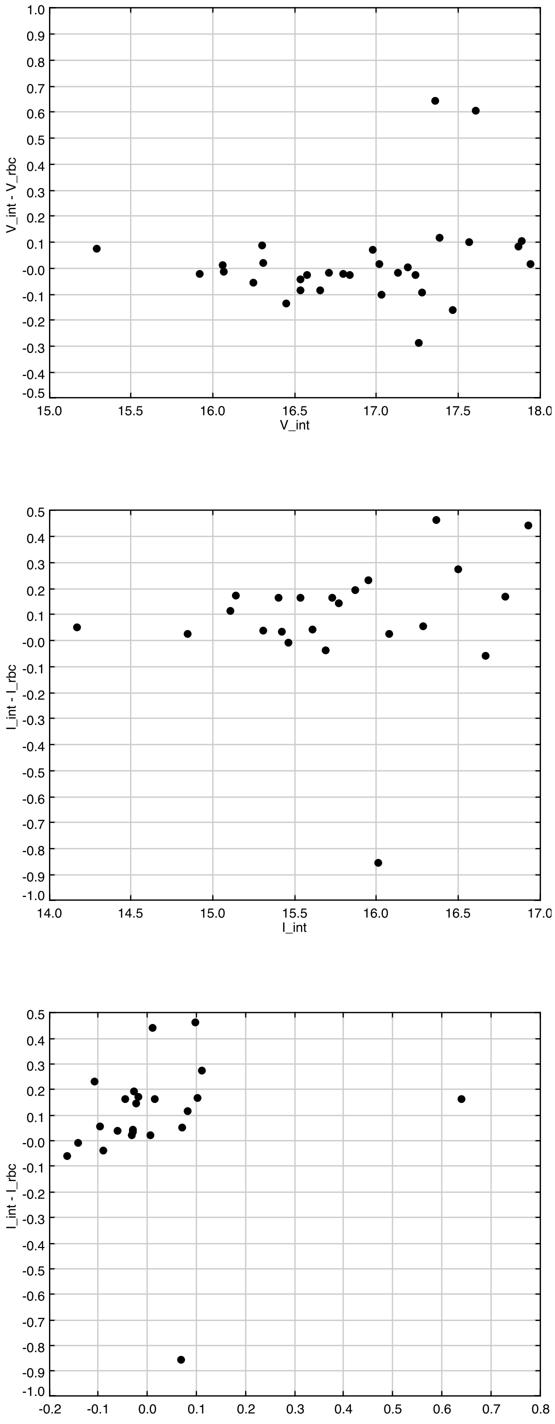

Figure 5. Residuals between new INT V and I band photometry, and published RBC values, and (lower panel) plot of v residuals against i residuals.

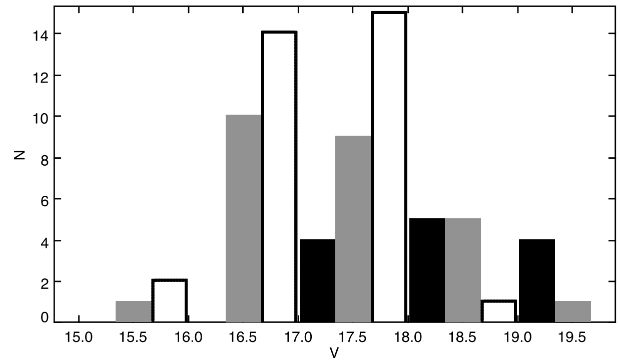

Figure 6. Histograms of apparent magnitude for confirmed RBC GCs in our survey area (open bars), and the newly found compact (grey bars) and extended (black bars) GCs.

spike from a nearby bright star. The 8″aperture was selected to allow direct comparison with the photometry of Barmby et al. (2000). Table 1 also gives (V-I) within a 6″radius aperture. This smaller aperture was used to reduce the error from the background and is valid assuming that no colour gradient is present in the clusters, For the extended clusters, the magnitudes were determined within a larger aperture of 12 arcsec radius which was judged to enclose the bulk of the light.

The INT/WFC survey uses Johnson V (V′) and Gunn i passbands hence a colour transformation was required to obtain the Johnson/Cousins equivalents V and I. This was done to allow for comparison of the GC photometry with other work. The transformations used are I = i - 0.101(V-I) and V = V′ - 0.005(V-I) (McConnachie et al. 2003). The CFHT Megacam data was transformed into the standard V and I system, from the Megacam g and i′ via the transformations:

$g_1 = g + 0.092$
$i_1 = i' - 0.401$
$(g - i) = g_1 - i_1$
$I = (i_1 - 0.401) - (0.08 \times (g - i)^2) + 0.06$
$V = g_1 - (0.42 \times (g - i)\ ) + (0.04 \times (g - i)^2) + 0.10$

Due to the high luminosity of the clusters, the formal errors reported by apphot are quite small. Indeed, the cluster magnitude uncertainties are dominated by the zero-point errors of ∼0.02 mag; colour errors are estimated to be ∼ 0.03 mag. This does not include errors due to contamination from foreground stars or background galaxies, as these are difficult to estimate.

We are confident that we exceed the RBC for depth. A plot of the V magnitudes for the newly discovered compact and extended clusters (6), shows that they reach fainter than the RBC GCs in the halo (beyond the visible disk). We would, however, still fail to find analogues of the very low luminosity GCs in the MW. For example, AM 4 would have a V∼ 22.9 at the distance of M31.

Table 3. Observation Log for UKIRT/UFTI and K-band magnitudes

Date	Target	Exposures (secs)	K_s
8th Aug. 2004	H2	5 x 36	15.12
	H5	5 x 24	14.14
	H6	5 x 24	13.50
	H7	5 x 36	15.41
	H8	5 x 180	15.66
	H10	5 x 24	13.81
	H14	5 x 36	15.07
	H19	5 x 36	15.24
	H23	5 x 24	14.18
	H24	5 x 36	15.17
9th Aug. 2004	H4	5 x 36	14.55
	H21	5 x 36	15.74
	H22	5 x 36	14.75

2.4.2 Near-IR Photometry

Near-IR photometry has been shown to be useful to reduce the age-metallicity degeneracy inherent in optical-only observations (Puzia et al. 2002). The majority of the new clusters have no 2MASS K-magnitudes and those that do are sufficiently faint that the 2MASS errors are > 0.15 mag. We thus embarked on a program to obtain near-IR photometry for a subset of the newly discovered clusters which we briefly summarize here. UKIRT/UFTI K-band observations were taken in queue mode on the 8th and 9th August 2004 (programme ID: U/04A/166, see Table 3 for details) using a JITTER_SELF_FLAT recipe. UFTI (Roche et al. 2003) is an IR imager, from 1-2.5μm, which has a field-of-view of only 92 arcsec across. Thirteen clusters were observed.

The data were reduced using standard ORAC-DR pipeline. In addition to the target clusters, a NIR standard star (FS103) was observed (5 x 5 second exposures) at the start and end of both nights. Aperture photometry, employing IRAF/apphot, and matching apertures with the optical photometry (8 arcsec), gave K-band magnitudes for the target clusters (see Table 3).

3 REVISION OF RBC

3.1 Checking of RBC candidate classifications

Due to the limited extent and contaminated nature of the existing catalogues, it was decided to use the INT/WFC and CFHT/Megacam surveys of M31 not only to search for new GCs in the outer halo, but to clarify the nature of many candidates from the earlier catalogues. In addition, other available archival imaging data was incorporated where available (e.g. the M31 POINT-AGAPE microlensing survey data (Calchi Novati et al. 2005) and the HST, CFHT/12K and Suprime-Cam archives).

For each RBC candidate beyond within our survey area (i.e. excluding the visible part of M31) we inspected all the imagery available to us. Table 4 notes those cases where this proccess led to an unambiguous amendment to the RBC classification. This table also lists the file names of the appropriate archive images to facilitate follow-up. In some cases, the status of a GC as confirmed is unchanged. In these situations, entries in Table 4 are only given where the new data improves significantly on that already available in the RBC. For example, if only a spectroscopic confirmation is given in the RBC we will note if new direct visual confirmation is available. This may seem unnecessary but we point out that M31 GCs do not always have radial velocities distinct from MW foreground objects hence morphological confirmation is valuable. Likewise, any instance where new imagery is of much higher quality than that previously used is also listed. Some of these amendments were also published in Galleti et al. (2007) however many revisions are reported here for the first time. We note that a number of "confirmed" halo GCs were found to be questionable in the INT data, and have been down-graded in this table from "confirmed" to candidate GC status. In these cases, the "confirmed" status came from radial velocity data only, but have values that are consistent with MW stars. They do not show clear GC morphology, and their flag in the INT-WFC pipeline reports them as stellar.

As can be seen from Figure 4, the INT-WFC survey contains almost all the known[2] halo GCs in the Revised Bologna Catalogue. It is thus possible to compare the INT/WFC photometry of the known GCs with that reported in the RBC. This enables a check on the RBC photometry – which has been drawn from a variety of sources, including photographic plates – and provides an improved and consistent set of photometry for all the GCs in the outer halo.

Photometry was obtained for all "confirmed" RBC GCs which lie outside the visible disk and which fall within in the WFC-INT M31 halo survey area using the procedures previously described. Table 5 presents the new photometry for these systems as derived from the INT/WFC survey. The depth of the exposures in the INT/WFC survey (typically 900 seconds) meant that the most luminous GCs were either at or close to saturation and there is no entry provided in the table. In other cases, the GC fell within the gaps between the four CCDs of the WFC.

A plot of the difference between the previously published RBC photometry and the new INT/WFC photometry is shown in Figure 5. The V-band values show typical residuals of $\pm$ 0. 1 mag, with two outliers. One of these is G260, which the INT/WFC imaging shows has two nearby stars, and may explain the offset from the RBC value. The I band shows a consistent positive residual, rising up to 0.5 mag for the faintest magnitudes, and with the expected increase in scatter (and with one outlier, B457, which also has an unlikely V-I value of 0.04 from the RBC). However, the RBC notes that most of its I band values are derived from scanned photographic plates and hence such errors are not unexpected. The good match between the RBC and INT/WFC V band photometry gives us confidence in the quality of the photometry of the new clusters.

4 SUMMARY

In this paper, we have presented the discovery of 40 new globular clusters found in the halo of M31, out to a galactocentric distance of ~ 100 kpc. Some of these these have been

[2] This study was completed prior to the publication of Kim et al. (2007), which are therefore not included in the RBC clarification process described in this section.

Table 4. Updates to the Revised Bologna Catalogue. The previous and revised classes are those used by the RBC: 1. confirmed GC, 2. candidate GC, 4. galaxy, 6. star. In addition, a new class, 8, shows objects that are blends of stars and/or galaxies. Note that there is frequently additional images available for any GC. That listed below is the image used for visual inspection.

ID	previous class	revised class	data source	comment
B029	1	1	STIS O8GOI7HJQ	
B045D	1	1(?)	ACS J92GA5NAQ	very compact, cluster?
B047D	1	6	ACS J92GB2HWQ	star, but faint, diffuse cluster nearby at 00:42:10.87 +41:29:58.5
B053	1	6	ACS J92GA1CYQ	
B054D	1	6	ACS J8VP04010	
B067D	2	1	ACS J92GB3DNQ	very small
B072D	2	4	ACS J92GB6ZLQ	most likely a background galaxy
B075	1	1	ACS J92GA5NBQ	previously only a spectroscopic confirmation
B080	2	1	ACS J92GA5NBQ	new confirmation
B091D	1	1	ACS J92GA7VMQ	previously only a spectroscopic confirmation
B097	1	1	ACS J92GA6ZIQ	
B098	1	1	ACS J92GA0C6Q	previously only a spectroscopic confirmation
B099D	2	4	INT	
B100	1	1	ACS J92GC3CSQ	
B101	1	1	WFPC2 U92GD101M	previously only a spectroscopic confirmation
B111	1	1	ACS J92GAC6Q	previously only a spectroscopic confirmation
B116	1	1	ACS J92GA3DLQ	previously only a spectroscopic confirmation
B122	1	1	ACS J92GA3DLQ	previously only a spectroscopic confirmation
B125	1	1	ACS J92GC1FKQ	previously only a spectroscopic confirmation
B135	1	1	ACS J92GA7VMQ	previously only a spectroscopic confirmation
B137	1	1	ACS J92GA7VMQ	previously only a spectroscopic confirmation
B141	1	1	ACS J92GA7VMQ	previously only a spectroscopic confirmation
B149	1	1	ACS J92GB7VOQ	previously only a spectroscopic confirmation, partly hidden by chip gap
B157	2	1	ACS J92GC2XJQ	new confirmation
B161	1	1	ACS J92GC2XJQ	previously only a spectroscopic confirmation
B164	1	1	ACS J92GD2XMQ	previously only a spectroscopic confirmation
B165	1	1	ACS J92GD2XJQ	previously only a spectroscopic confirmation
B175D	2	4	INT	shows object as a galaxy
B180	1	1	ACS J92GC6D1Q	previously only a spectroscopic confirmation
B182	1	1	ACS J92GC6D1Q	previously only a spectroscopic confirmation
B202D	2	4	INT	a fine spiral galaxy
B227D	2	4	INT	image shows spiral galaxy
B229D	2	6	CFHT12K Stream-7	
B234D	2	4	INT	a spiral galaxy
B266	2	1	ACS J92GB4E7Q	new confirmation
B272	1	1	ACS J92GA8VUQ	
B289D	1	2	INT	
B292D	1	2	INT	
B298	1	1	ACS J96G11010	cluster GC6 in Mackey et al. (2006)
B301	1	1	CFHT12K 550666p	previously only a spectroscopic confirmation
B305	1	1	In CFHT12K 550666p	previously only a spectroscopic confirmation
B309	1	1	In CFHT12K 550666p	previously only a spectroscopic confirmation
B350	1	1	CFHT12K Stream-8	
B357	1	1	CFHT12K Stream-8	previously only a spectroscopic confirmation
B379	1	1	ACS J8F857010	
B407	1	1	ACS J8DB07010	
B427	2	4	INT	shows a blend of 2/3 galaxies
B443	1	8	INT	blend of three objects
B451	1	8	INT-WFC	appears to show a double star
B453	1	8	INT	blend of two stars
B463	2	4	CFHT12K Stream-8	
BA11	1	2	INT	galaxy?
BH20	2	6	ACS J8F101MRQ	
G003	1	8	INT	blend of three objects
NB29	2	2	ACS J8VP04010,	asterism?
V234	2	1	STIS O4XCJ4ZZQ	

Table 5. New Photometry of Known RBC Clusters

ID (from RBC)	V (mag)	(V-I)
B150D	17.26	0.89
B167D	17.87	0.93
B289	16.07	0.93
B290	17.03	1.08
B291	16.54	1.00
B293	16.31	0.91
B295	16.66	0.97
B298	16.45	0.99
B314	17.47	0.80
B337	16.71	0.94
B339	16.84	1.23
B343	16.25	0.94
B344D	17.02	0.99
B357	16.58	1.16
B358	15.29	1.12
B365	17.36	1.63
B396	17.28	0.99
B398	17.57	1.20
B399	17.39	0.89
B401	16.80	0.93
B402	17.24	1.16
B403	16.30	1.19
B407	16.06	1.21
B422	17.94	1.01
B457	16.98	0.97
B468	17.89	1.10
DAO25	18.87	1.14
G260	17.61	1.59
G268	16.54	1.19
G327	15.92	0.97
G339	17.19	1.03
G353	17.13	0.92

published by us elsewhere but in this paper we present all the new GCs for the first time. They considerably increase the number of known GC in the far halo. Of the 40 new clusters, 13 are found to be of an extended nature. The new clusters are found all the way to the edge of the survey area, strongly suggesting that others await discovery much further out. Indeed, a search for new dwarf galaxies in an extension to the Megacam survey used here has already found a luminous GC that is, to date, the most distant known from the center of M31 (Martin et al. 2006). A future paper will take these new GCs, and the recent updates to the RBC, to investigate the properties of the whole GC system of M31 and the implications for our understanding of the history of system.

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